This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161

Redirection Detection Thresholds for Avatar Manipulation with Different Body Parts

Ryutaro Watanabe*, Azumi Maekawa*, Michiteru Kitazaki, Yasuaki Monnai, Masahiko Inami

Abstract—This study investigates how both the body part used to control a VR avatar and the avatar's appearance affect redirection detection thresholds. We conducted experiments comparing hand and foot manipulation of two types of avatars: a hand-shaped avatar and an abstract spherical avatar. Our results show that, irrespective of the body part used, the redirection detection threshold increased by 21% when using the hand avatar compared to the abstract avatar. Additionally, when the avatar's position was redirected toward the body midline, the detection threshold increased by 49% compared to redirection away from the midline. No significant differences in detection thresholds were observed between the hand and foot manipulations. These findings suggest that avatar appearance and redirection direction significantly influence user perception in VR environments, offering valuable insights for the design of full-body VR interactions and human augmentation systems.

Index Terms—Virtual reality, hand redirection, detection thresholds

1 Introduction

Humans use various parts of their bodies to provide motion input for operating devices and machines in our daily lives. While hands are most commonly employed for this purpose, other body parts are also effectively utilized depending on the situation. For example, driving a car involves using hands to control the steering wheel and buttons, while the feet manage the car's acceleration and braking. In the research field, body augmentation systems that leverage motion input from the feet have begun to be proposed [35, 36]. Designing interfaces tailored to the specific body part has the potential to offer optimal performance and interaction in both real-world and virtual environments.

One crucial design element is how to map user motor inputs to the corresponding operations. Various interactions can be achieved depending on the mapping methods, a technique often referred to as *redirection*, *remapping*, or *retargeting*. For example, by shifting the virtual objects or avatar's movements in response to the user's actual movements, it is possible to effectively utilize real objects in virtual reality (VR) [21, 38] and support intuitive control of robotic arms in the real world [32].

Such redirection techniques are based on the effect of visual dominance [34], where visual information takes precedence when integrating and processing multiple sensory inputs. However, if the discrepancy between visual information and other sensory inputs, such as proprioception, becomes significant, this discrepancy can no longer be ignored, leading to a sense of discomfort for the user. Therefore, understanding the threshold limits for redirection that avoid such conflicts is crucial for designing systems and many researchers have been investigating these limitations [12, 40].

However, while extensive research has been conducted on redirection in hand-based interactions, the relationship between proprioception and redirection for other body parts remains unclear. In fact, it has been reported that proprioception varies between different body parts [11], and effectively utilizing these differences could provide design guidelines for control inputs using various body parts such as the feet [36] or head [16].

In this study, we focus on the influence of feet use on the detection thresholds for redirection. Additionally, since the appearance of the avatar which the movement is mapped can also influence these detection thresholds [30], we investigate interactions between the appearance and body parts used for the movements. As depicted in Figure 1, we compared reaching tasks performed with the hand and foot. The participants performed reaching tasks in a VR environment using their dominant hand and foot with two types of VR avatar appearances: 1) a hand-shaped avatar and 2) an abstract sphere as shown in Figure 2. While the participants performed the reaching movements, the virtual avatar was shifted horizontally to the left or right at different angles. In this setup, to standardize the visual conditions, the starting position of the VR avatar's movement was vertically offset so that its vertical position aligned with the participant's eye level. Afterward, participants were asked to identify whether the observed movement was consistent

Fig. 1: The redirection detection task conducted in the VR space. Participants used different body parts (their hand and foot), to manipulate a VR avatar and perform reaching movements, with the motion being shifted left or right depending on the experimental condition.

- *Ryutaro Watanabe is with the University of Tokyo. E-mail: ryutarowatanabe@star.rcast.u-tokyo.ac.jp*
- *Azumi Maekawa, Yasuaki Monnai, and Masahiko Inami are with Research Center for Advanced Science and Technology, the University of Tokyo. E-mail: azumi@star.rcast.u-tokyo.ac.jp, monnai@star.rcast.u-tokyo.ac.jp, and inami@star.rcast.u-tokyo.ac.jp*
- *Michiteru Kitazaki is with Toyohashi University of Technology. E-mail: mich@tut.jp*
- *∗ These authors contributed equally to this work*

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161

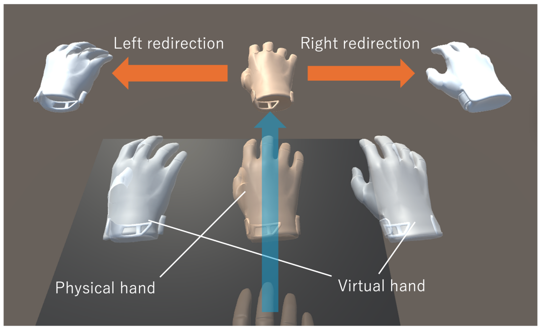


Fig. 2: Participants conduct a reaching task with visual feedback of a human hand-shaped avatar (hand avatar) or spherical avatar (abstract avatar) to which horizontal shifts are incrementally applied. The hand moving straight along the depth direction from front to back in the center (indicated by the blue arrow) represents the actual movement of the participant's body part used to operate the avatar (not displayed in the actual experimental scene).

with their actual movement. We also measured the subjective evaluation of the sense of embodiment to further investigate participants' experiences. The results showed that the detection thresholds for redirection was significantly larger when a hand-shaped avatar was used than when an abstract avatar was used, while there was no significant difference on the detection thresholds for redirection by the difference of the body part to be manipulated. The result also showed that when the VR avatar was redirected medially, the threshold was larger than when the VR avatar was redirected laterally, regardless of the body part used for manipulation.

2 Related Work

2.1 Motor Input from Various Parts of the Body

We use various body parts to operate devices in our daily lives. In the fields of Human-Computer Interaction (HCI), robotics, and VR, while many operation methods using the body involve hands, recently, alternative methods utilizing other body parts have also been proposed. For example, methods to control supernumerary robotic limbs, which are wearable robotic arms, using motion input from the legs [1, 35, 36], shoulders [37], or face [6, 7] have been proposed. Methods for controlling wearable robotic fingers, which are attached to the user's hand, include using both big toes [17] or utilizing forearm co-contraction [39] to operate the device. Motion input from body parts other than the hands has been utilized not only for wearable robots but also for robots fixed to the environment. Jackowski et al. developed a system that uses head movements to control a six-degree-of-freedom robotic arm for motion-impaired people [16]. Hernandez Sanchez et al. proposed a system that uses foot movements to control a robotic arm, enabling four-armed surgery by combining the operator's two arms with the robotic arms [15].

While these previous studies have proposed various control methods using different body parts, there is a lack of studies on approaches that combine such non-hand body parts with redirection, as well as on the perceptual thresholds of users for this redirection. We focus on the user experience in redirection involving movements using the feet, and compare it with the case of using the hands.

2.2 Visual Dominance and Redirection

It is known that the human senses are visually dominant, meaning that when there is a conflict in integrating multiple senses, vision is often given priority [34]. For example, when objects or movements are visually distorted, there is a phenomenon where the users can perceive surfaces as curved [3] or feel a difference in rigidity compared to the actual physical properties [25]. Techniques known as redirection and retargeting utilize this visual dominance approach. Methods combining these techniques with various movements such as hand movements [20], walking [33], and jumping [14] have been proposed. This allows for effective use of physical resources, such as real space and objects [2], to guide movement toward a target [20]. Additionally, the concept of redirection, which involves shifting the correspondence with the user's actual movements, is used not only in avatars within virtual reality but also in real-world robot operation. For example, Rakita et al. proposed an intuitive method of robot operation by allowing a misalignment between the user's arm movement and the robot arm's movement [32].

However, if visual feedback is excessively modulated, the discrepancy with other sensory information, such as proprioceptive sensation, increases, and the user feel uncomfortable. Therefore, researchers have been investigating the extent to which users can perceive the motion as their own motion without discomfort. For example, in a study by Zenner et al. [40], they reported that redirection within an angle of 4.5° to the left and right and a distance range of -6.18% to +13.75% was found to be imperceptible to the user. To ensure that the users do not feel uncomfortable with redirection, it is necessary to properly understand the limits of how much visual information can be modulated. Furthermore, it has been suggested that the appearance of the avatar itself can also influence the detection threshold for redirection [30], indicating that it is necessary to consider various factors, not just displacement from the original movement.

2.3 The sense of Embodiment

Sense of Agency (SoA) refers to the sense that "a certain action was caused by my intention" and Sense of Body Ownership (SoBO) refers to the sense that "it is my body that is having a certain experience. [8, 10, 39]. The Sense of Embodiment (SoE) is the synthesis of the SoA and the SoBO, plus the sense of self-position, which is the sense that one's position exists in the position where the object exists. [18]. SoA and SoBO are widely used as metrics to evaluate users' experiences and impressions in virtual reality environments. For example, Debarba et al. conducted hand redirection in a VR environment, investigated the sense of self-attribution regarding the movements, and discussed the relationship between redirection and SoA [4]. Kondo et al. assigned the movements of the first and second joints of the right thumb to the elbow and shoulder movements of the left arm avatar in VR space, respectively [22]. When the movements of the VR avatar of the left arm were synchronized with the movements of the right thumb, a higher SoBO was obtained than when the movements were not synchronized. In addition, when the movements of the first and second joints were reversed and assigned to the shoulder and elbow movements of the left arm avatar, or to the elbows of the left and right arms, no SoBO was generated.

Previous research has suggested a correlation between the SoE and the appearance of VR avatars. For example, Kilteni et al. [19] reported that the closer the avatar is structurally and morphologically to its own body, the higher the SoBO. More recently, it has been suggested that increasing the realism of an avatar enhances the SoE [41].

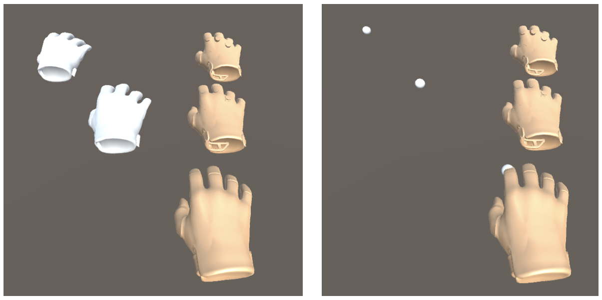
Researchers have also investigated the relationship between redirection techniques and the SoE under several conditions. For example, Ogawa et al. [30] suggested that the closer the VR avatar's appearance was to the shape of a human hand (more realistic), the larger the redirection detection threshold. Although this experiment did not confirm differences in the SoE based on avatar appearance, more recent studies have reported contradictory findings. For example, while the realism [13] and completeness [5] an avatar were found to enhance SoE, no significant effect was observed on the redirection detection threshold. The relationship and mechanisms underlying these effects not fully understood.

As discussed in these studies, the sense of embodiment are important considerations when designing VR interactions. To gain deeper insights into users' subjective experiences, we also conduct an investigation related to the sense of embodiment.

3 Experiment

The main purpose of this experiment was to investigate the differences in detection thresholds for redirection depending on the body part used to operate the VR avatar and the appearance of the avatar. To

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161



(a) Hand avatar (b) Abstract avatar

Fig. 3: The colored hand avatar indicates the movement of the real body part, while the white-colored avatar indicates the appearance and the redirected movement of the VR avatar that the user controls in the VR space. We have prepared two types of avatars: (a) a VR avatar in the shape of a hand (hand avatar) and (b) a VR avatar in the shape of a sphere corresponding to the position of the index finger of the hand avatar (abstract avatar). Collision detection is set to either the tip of the index finger or the same size sphere.

further explore this difference based on the user's experience, we also investigated the subjective evaluation of embodiment for the VR avatars under each condition.

In the experiment, participants wore a head-mounted display (HMD) and, while seated, performed reaching tasks in which they touched objects displayed in the VR scene by operating the VR avatar. In each trial, participants operated the VR avatar using different body parts, either their hand or foot. As shown in Figure 3, the appearance of the VR avatar was either a hand-shaped avatar or a sphere, as described in section 3.1, and participants operated one of these VR avatars in each trial. During the reaching motion, the position of the VR avatar was shifted from the position of the real body according to the redirection model explained in section 3.3. The participants were asked whether the movement of the VR avatar matched their actual movement in each trial. After completing the task, participants answered a questionnaire regarding embodiment. The experimental process and details of each trial are described in section 3.6 and 3.7.

3.1 Avatar Appearance

We prepared VR avatars in two different appearances as shown in Figure 3. The hand avatar is an avatar in the shape of a hand. The abstract avatar is a white spherical appearance with a position and size (0.05 m) corresponding to the tip of the index finger of the hand avatar. In order to unify the color conditions of the VR avatars, the hand avatar was covered with a white texture over the entire surface. We set the hand avatar to take the shape of the right hand when operated with either the right hand or right foot, and the shape of the left hand when operated with the left foot. The fingers of the hand avatar were fixed, and the participants controlled only the spatial position of the hand. We did not use foot-looking avatar because the main goal of this study was to investigate the effect of different body parts on the detection threshold.

Collision detection (the ability to react when objects collide) for the abstract avatar was implemented as a sphere of the same size as the avatar, a sphere with a diameter of 0.02 m, ensuring that the entire avatar serves as the collision detection area. On the other hand, the hand avatar has collision detection only on the tip of the index finger. The position and size of the part of the avatar with collision detection are the same regardless of the avatar's appearance. When performing the task with the hand avatar, the participant was informed in advance that they would have to touch the object with the tip of the index finger to get a reaction.

3.2 VR scene of experiment

Figure 4 shows a scheme of the disposition of objects in the VR scene of the experiment. The VR scene for the task was arranged with a panel

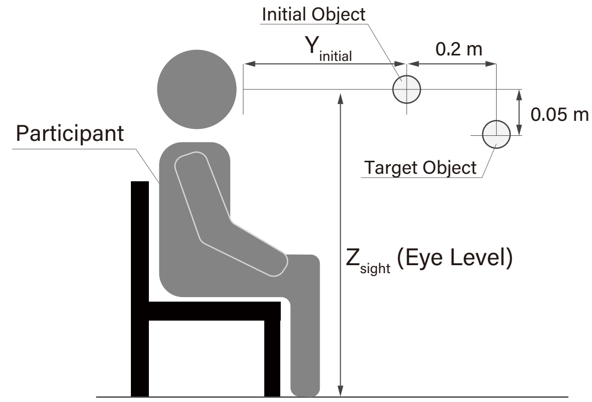


Fig. 4: Scheme of the disposition of objects. The target object is a spherical object with a diameter of 0.05 m placed 0.2 m behind and 0.05 m below the initial position. At the start of the experiment, only the initial object (a spherical object with a diameter of 0.05 m in the foreground) is visible. This group of objects was set based on the eye height Z_{sight} according to the offset model in section 3.4. The depth $Y_{initial}$ was also set so that the participant could touch both the initial object and the target object with the avatar.

with the initial object (a spherical object in the foreground), the target object (spherical object in the background) and a question text. The target object was set 0.2 m further and 0.05 m lower than the initial object. The initial object and the target object were the same appearance. Both objects were 0.05 m in diameter, and white in appearance. The distances were determined based on preliminary experiments so that the seated participants could touch both the initial object and the target object. For the VR scene of the embodiment questionnaire, a panel with the questions was placed so that the participant could see it.

The VR avatar operated by the participant and the group of objects in the VR scene were placed so that they were at the same height as the eye level according to the offset model 3.4. We used this offset model to eliminate the visual effects caused by differences in the avatar's vertical position and to standardize the visual conditions between the hand-operated and foot-operated conditions.

The relative positions of the initial object and the target object did not change. When the operation was performed using the hands, all participants were able to touch both objects at a depth setting of 0.35 m for the initial position and 0.55 m for the target object, so the experiment was conducted using this setting. On the other hand, when manipulation was performed using the feet, the range of motion of the feet differed for each participant, so the initial position and target object were adjusted according to the participant so that both objects could be touched with the feet.

3.3 Redirection Model

In the redirection detection task, horizontal redirection proportional to depth was performed, as used by Zenner et al. [40] and Ogawa et al. [30]. The VR avatar was redirected so that, with respect to the initial position, the VR avatar was shifted left or right relative to the body part used for the manipulation in proportion to its approach to the depth of the target object. Figure 5 shows the redirection model used when shifting the position of the VR avatar to the left. Taking the participant's head position as the origin, with left/right direction as the X-axis and front/back direction as the Y-axis, $Y_{initial}$ represents the Y-position of the initial object, and T_{goal} is the redirected distance along the X-axis when the VR avatar reaches the Y-position of the target object. The shift distance $T_x(y)$ in the X-direction at the Y-position of the VR avatar can be expressed as follows:

$$T_x(y) = \begin{cases} 0 \quad (y < Y_{initial}) \\ \dfrac{T_{goal} * (y - Y_{initial})}{d} \quad (y \geq Y_{initial}) \end{cases}$$

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161

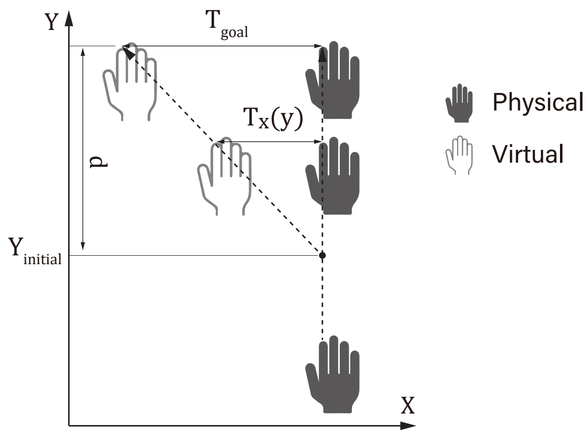


Fig. 5: Horizontal redirection of the VR avatar relative to the body part used for the reaching task. This redirection was done only during the redirection task. The black hand indicates the position of the body part being manipulated and the white hand indicates the position of the VR avatar. Up to the depth of the initial position, the horizontal positions of the body part and the VR avatar are identical. At a point deeper than the initial position, the VR avatar drifts to the left or right in proportion to the depth of the body part.

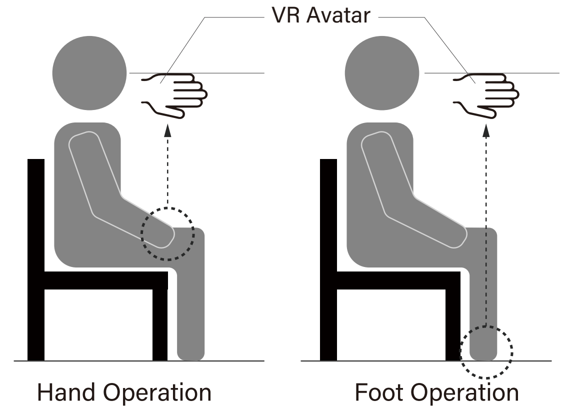


Fig. 6: Vertical offset was performed at the start of the experiment. The offset was applied only in the vertical direction, ensuring that the vertical position of the VR avatar at the start of the experiment was at the participant's eye level, regardless of the position of the body part used for the manipulation. This offset was applied at the beginning of the experiment for each participant.

In other words, redirection was not applied at positions closer than $Y_{initial}$ in the depth direction. When the VR avatar was moved behind the initial object's position, its X position was redirected linearly so that it shifted by T_{goal} at the location of the target object, which is at a distance d behind $Y_{initial}$. The distance d was set to 0.2 m as described in the previous section, and T_{goal} was varied depending the trials.

3.4 Offset Model

To maintain consistent visual conditions, we adjusted the initial position of the VR avatar so that the participant could touch the VR object set in the same position, regardless of which body part was used to perform the manipulation. Therefore, a vertical offset was applied to the VR avatar's position relative to the position of the body part used for the operation, so that both the height of the VR avatar and the target object matched the participant's eye level, as shown in Figure 6.

This offset was adjusted at the begininng of the VR scene and had no effect on the VR avatar's movement thereafter. This offset was made in both the redirection detection task and the embodiment questionnaire. This offset was adjusted at the beginning of the VR scene to match the participant's operating body part and eye level. For example, if the height of the body part used for the operation is 0.3 m in a normal state and the eye level is 0.9 m, the position of the VR avatar is set 0.6 m above that body part at the start of the VR scene.

3.5 Participants

The effect size was estimated to be Large based on previous studies [30]. Before conducting the experiment, G*Power was used to calculate the number of participants required to estimate the effect size as 0.8, the significance level as 0.05, and the power as 0.8. The results showed that a minimum of 12 participants were required to participate. Therefore, 18 participants (14 males and 4 females), ranging in age from 21 to 33 years (median = 23.0 years, mean = 24.0 years), participated in the experiment. 15 participants were right-handed, 3 left-handed. 14 were dominant on the right foot, 2 on the left, and 2 ambidextrous. Participants' heights ranged from 154 cm to 180 cm (median = 173.0 cm, mean = 170.3 cm). However, one of them could not obtain accurate data due to an error in the experimental program and had to be excluded from the experimental results, so the remaining 17 participants were used as the data for this experiment.

In this experiment, the dominant hand was determined based on the participant's self-report. However, the concept of a dominant foot is less common than that of a dominant hand, and in some cases, the self-identified dominant foot may differ from the foot that actually exhibits superior movement or sensation. Therefore, in this experiment, we determined the dominant foot by having participants perform a one-legged jump, following the method described in [23], and identifying the foot they used as their dominant foot. The participants were paid 2,240 yen (Approximately $15)Amazon gift cards. This experiment was conducted with the approval of the Life Science Research Ethics and Safety Office at the University of Tokyo, Japan (approval number: 22-389). All participants provided informed consent prior to the experiment.

3.6 Redirection Detection Task

Figure 7 depicts the trial process of the redirection detection task. The task was performed according to the following procedure:

1) Before starting the task, participants performed reference positioning (resetting the initial position and angle of the VR headset) and height adjustment (aligning the target object and the VR avatar to be manipulated with the participant's eye level while seated).

2) The participants touched the initial object with the avatar. 3) Then a beep sounded and the initial object turned red, and participants held the avatar in that position for one second until the next beep sound.

4) When the next beep sounded, the initial position disappeared and the target object appeared. Participants moved their VR avatars to touch the target object for one second before the next beep. 5) When the target object was touched, its color turned red. After one second elapsed, a beep sounded regardless of whether the participants were able to touch the target object, and the participants automatically moved to the next phase.

6) After the beep, the target object disappeared and the initial object reappeared. The participants then retracted the VR avatar and touched the initial object again.

7) The initial object disappeared and the question panel appeared. The following question was presented in Japanese on the question panel: “"Did the movement of the VR hand (the sphere) correspond accurately to the movement of your actual body?” If the participants felt that the VR avatar's movements in 3) and 4) matched that of the body part to be manipulated in the real world, they selected "YES" with the A button on the controller. If they felt that they did not, they selected "NO" with the B button and confirmed their selection with the trigger. Participants were free to change their answers until the selection was confirmed. In

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161

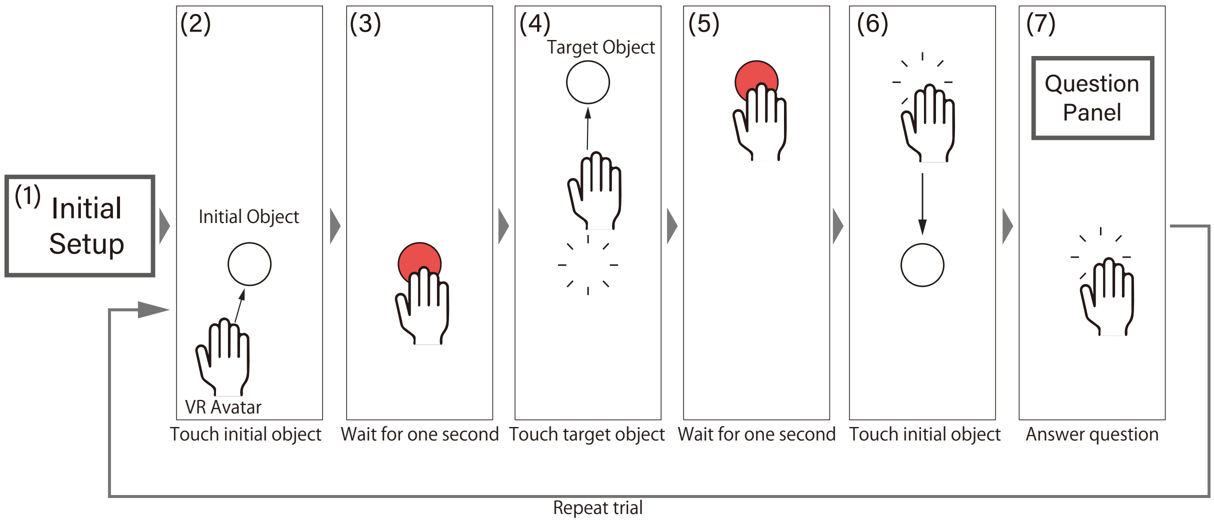


Fig. 7: Illustration of the trial process. 1) After the initial setup, including adjustments to the avatar's initial position and the HMD, 2) the participant touches the initial object. 3) After waiting for one second, 4) they reach for the target object that appears, 5) touch it, and wait for one second. 6) Then, they touch the initial object that reappears, and 7) answer whether the avatar followed the movements of their body part. Participants repeat this process.

this case, the participants were told in advance not to consider the shift of the vertical offset.

Participants returned to 2) again and repeated trials 2) - 7). The trials were performed continuously, but participants were free to take breaks between trials. The experiment took about an hour per participant in total. Participants performed the task in all experimental conditions for each avatar type, body part to be controlled, and redirection direction. Note that while the avatar and redirection direction were randomized, the order of the body parts to be controlled was not randomized.

3.6.1 Staircase Procedure

We investigated the participants' detection thresholds using the staircase method. The staircase method is an adaptive measurement method used in psychophysics to detect thresholds (absolute thresholds). In this method, the initial stimulus level and the amount of change in the stimulus are set as starting values, and the stimulus level is adjusted according to the results of the trials (yes/no). If the trial result changes during the trial, the direction of stimulus change is reversed. The experiment concludes when the number of reversals reaches a predetermined count or when the total number of trials reaches a set limit, regardless of the number of reversals. In this experiment, the staircase method was terminated after six reversals, and the threshold was calculated by averaging the stimulus levels at the points of reversal.

This method allows for multiple trials near the threshold, which is advantageous. However, it also has the disadvantage that participants' knowledge and strategies can influence the results. For instance, if participants are familiar with the staircase method, they can end the experiment more quickly by alternating their responses between "yes" and "no." In this experiment, the interleaved staircase method was used under four conditions based on the direction of redirection (left/right) and the appearance of the avatar. The interleaved staircase method involves conducting two staircases simultaneously: one ascending series (starting with a stimulus level below the assumed threshold) and one descending series (starting with a stimulus level above the assumed threshold). Because participants do not know which series is being conducted at any given time, the interleaved staircase method helps mitigate the problem of participant bias, thereby increasing the reliability of the measurements.

In this experiment, the eight staircase methods were performed simultaneously in a randomized order. For the left-right displacement stimulus when the target object was reached (i.e, T_goal in Figure 5), the initial stimulus level for the ascending series was set to 0 mm, and the initial level for the descending series was set to 200 mm, with the amount of change set at 30 mm. Participants completed the first trial of each of the eight staircases in randomized order, then proceeded with the second trial of each staircase, and so on.

We also measured the subjective evaluation of the sense of embodiment, which included a sense of agency (SoA) and a sense of body ownership (SoBO), by means of a questionnaire based on the Gonzalez-Franco et al [9]. The questions in the embodiment questionnaire were translated into Japanese, and questions unrelated to this experiment, such as those related to tactile sensations, were excluded.

The embodiment questionnaire was administered on a VR scene. As in the redirection detection task, participants wore a motion tracker on their right hand or right foot and a VR controller on their left hand while wearing the HMD. The question set consisted of 9 questions, one for each of the real and abstract avatars, for a total of 18 questions. The order in which questions were asked from the question set was completely randomized; the VR avatar's appearance switched to the corresponding appearance for each question. The VR avatar was also vertically offset in this situation so that its vertical position was at eye level. This was to ensure that the distance from the avatar's eyes is consistent across conditions, thereby reducing the influence of visual differences on the experimental results.

Participants answered the questionnaire purely by observing the appearance and movement of the VR avatar, without considering the content or impressions of the previous redirection detection task. Participants responded to the questions on a 7-point scale from -3 (strongly disagree) to +3 (strongly agree) by operating the controller.

3.7 Procedure

The experimental procedure was conducted in the following order: 1) Redirection detection task 2) Embodiment questionnaire.

The redirection detection task was performed by manipulating the VR avatar in the order of the right hand, right foot, and left foot. In this experiment, the left hand was used to hold and operate the VR controller for answering the displayed questions; therefore, avatar manipulation using the left hand was not conducted.

In the embodiment questionnaire, participants answered the questions by manipulating the VR avatar in the order of right hand and right foot. In both processes, participants were given sufficient time at the start to practice the tasks and questionnaires, and to adjust the

Table 1: Questions for the embodiment questionnaire based on [9] (questions in bold are Control Questions)

Subscale	Question
Ownership	I felt as if the VR avatar was my hand (foot).
	It felt as if the VR avatar I saw was someone else.
	It seemed as if I might have more than one hand.
Agency	It felt like I could control the VR avatar as if it was my own hand (foot).
	The movements of the VR avatar were caused by my movements.
	I felt as if the movements of the VR avatar were influencing my own movements.
	I felt as if the VR avatar was moving by itself.
Location	I felt as if my hand (foot) was located where I saw the VR avatar.
	I felt out of my body.

headset's eye-to-eye distance and alignment as needed. The detailed experimental procedure is presented below.

1. Signed the consent form and acknowledgement receipt.
2. Listened to an explanation of the experimental task and questionnaire.
3. After practicing the redirection detection task, the participants completed the task.
4. The embodiment questionnaire was administered.
5. The participants answered a questionnaire about their age, height, dominant hand, and dominant foot.

The entire experiment took about one hour.

3.8 Apparatus

The experimental system was controlled by a Windows 10 PC from Razer Inc. (Intel(R) Core(TM) i7-9750H CPU @ 2.60GHz, 16.0 GB RAM)." Apparatus for VR tracking included a Valve Index HMD from Valve Corporation, a Valve Index controller, a SteamVR Base Station 2.0 and Vive Tracker 3.0. The Base Station was placed on the floor with a tripod. The tracker was attached to a Velcro strap, which was wrapped around the participant's wrist or the top of the foot to secure it to their body. The positions of body parts were measured by the tracker and reflected in the positions of the VR avatars using the redirection model described in the section 3.3 and the offset model in the section 3.4.

3.9 Hypothesis

In this experiment, we tested the following hypotheses. We hypothesized that redirection might be less detectable in the foot-operated condition, based on previous research suggesting that detection thresholds increase when the avatar's appearance is close to a real hand, e.g., [30], and the empirical observation that people are generally less accustomed to manipulating objects with their feet compared to their hands.

1. The detection threshold for redirection is larger when VR avatars are manipulated using feet than when VR avatars are manipulated using hands
2. The detection threshold for redirection is larger when hand avatars are used than when abstract avatars are used
3. SoBO of the avatar is smaller when a foot is used to manipulate the VR avatar than when a hand is used to manipulate the VR avatar
4. SoBO of an avatar is smaller when manipulating an abstract avatar than a hand avatar

4 Results

In cases where the experimental data normal distribution assumption (Shapiro-Wilk's normality test) was not violated ($p > 0.05$), repeated analysis of variance (ANOVA) was performed. Finally, Tukey-kramer multiple comparisons were performed to confirm the superiority of one-to-one comparisons for parametric tests. In addition, ${\eta_p}^2$ was used to quantitatively compare effect sizes.

In cases where the normal distribution assumption was violated, a Wilcoxon signed rank test was performed.

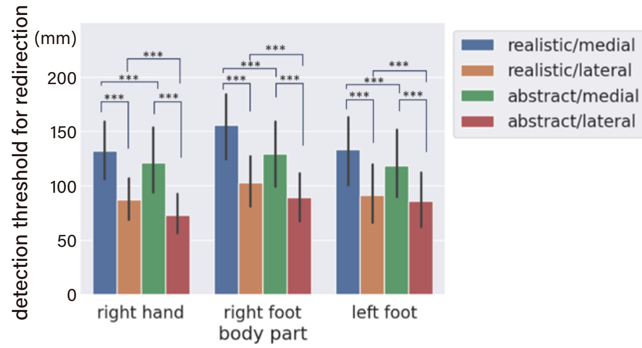


Fig. 8: Results of the redirection detection task. Each bar plot indicates a combination of the avatar's appearance (either the hand avatar or the abstract avatar) and the direction of the shift (shifted medially or laterally from the participant's perspective), while the horizontal axis indicates the body part used for the manipulation. Error bars represent standard errors. ***: $p < 0.001$.

4.1 Redirection Detection Task

To test Hypothesis 1 (the detection threshold for redirection is larger when VR avatars are manipulated using feet than when VR avatars are manipulated using hands) and Hypothesis 2 (the detection threshold for redirection is larger when hand avatars are used than when abstract avatars are used), we analyzed data from the redirection detection task. Because the experiment was conducted using the interleaved staircase, the average of the two results in the ascending and descending systems was used as the representative value. The results of the staircase method itself were the average of six redirection distances at the point where the responses to the questions were reversed. It should be noted that the data analysis was conducted using the criterion of medial/lateral as the redirection direction. For the right hand and right foot, *medial* refers to the left direction and *lateral* to the right direction, while for the left foot, *medial* refers to the right direction and *lateral* to the left.

As a result, as shown in Figure 8, when the avatar condition was changed [$F = 17.56,\ p < 0.001,\ \eta_p^2 = 0.527$] and the shift direction was changed between medial and lateral [$F = 23.72$, $p < 0.001$, $\eta_p^2 = 0.597$], the null hypothesis was rejected, indicating a significant difference. On the other hand, no significant difference was detected [$F = 2.70$, $p = 0.083$, $\eta_p^2 = 0.145$] when the body parts used for the manipulation was changed. These interactions were not significant. Tukey-kramer multiple comparison tests were conducted for the two conditions in which significant differences were detected, and significant differences were detected in both conditions.

We also analyzed the extent to which threshold for redirection was relatively different between the hand and abstract avatar conditions. The participant's threshold for redirection with the hand avatar under the same conditions was divided by the threshold for redirection with the abstract avatar. These values were classified by the body part used and the medial/lateral redirection direction.

When repeated analysis of variance (ANOVA) was performed, the null hypothesis of no difference in means under different conditions was not rejected. The threshold for redirection for the hand avatar was 1.21 ± 0.14 times (95% confidence interval) the threshold for redirection for the abstract avatar. Similarly, the threshold for redirection for the medial redirection was 1.49 ± 0.01 times (95% confidence interval) that of the threshold for redirection for the lateral redirection.

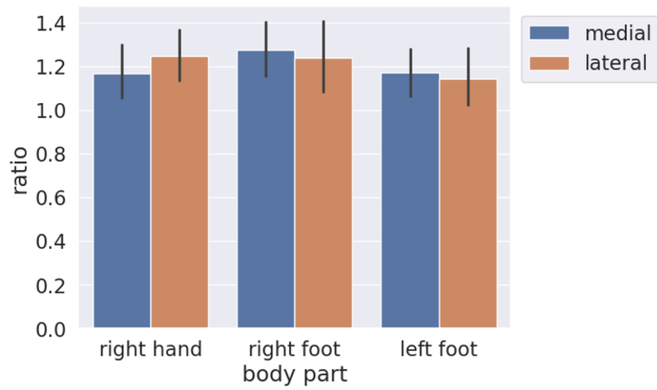


Fig. 9: The ratio of the threshold for redirection of the hand avatar to the abstract VR avatar for the redirection task. The condition on the horizontal axis indicates the combination of the body part to be used and the redirection direction. Error bars represent standard errors.

From the above, although hypothesis 1 could not be supported in the redirection detection task, hypothesis 2 was supported. In other words, while there was no significant difference in the threshold for redirection when the body part used to manipulate the avatar was changed, the threshold for redirection was higher when the hand avatar was used compared to the abstract avatar was used. This effect was confirmed for both limbs.

4.2 The Embodiment Questionnaire

Figure 10 shows the result of the embodiment questionnaire. To test Hypothesis 3 (SoBO of the avatar is smaller when a foot is used to manipulate the VR avatar than when a hand is used to manipulate the VR avatar) and Hypothesis 4 (SoBO of an avatar is smaller when manipulating an abstract avatar than a hand avatar), the results of the embodiment questionnaire were analyzed. The results of the embodiment Questionnaire from -3 (strongly disagree) to 3 (strongly agree) were averaged for each subscale. In this case, the value of the Control Question was multiplied by -1. The average value of each subscale was used as the representative value for the analysis.

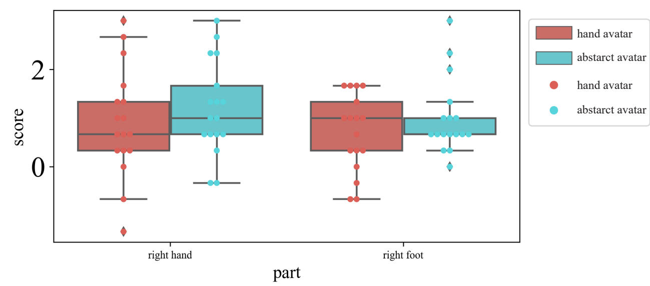
The Agency subscale for the right-hand-operated and abstract avatar, and the Ownership and Location subscales for the right-foot-operated and abstract avatar, were found to violate the normal distribution assumption (Shapiro-Wilk's normality test) ($p < 0.05$).Therefore, the Wilcoxon signed rank test, a nonparametric test, was conducted for each pair. The results showed a significant difference ($p = 0.0458$) between the hand and abstract avatar on the Agency subscale only when the avatars were operated with the right hand. However, no significant differences were found between the other conditions.

In summary, hypothesis 3 was not supported for the embodiment questionnaire, but hypothesis 4 was partially supported. In other words, no change in SoBO due to changing the body part used for manipulation was observed on any of the subscales. However, only when manipulation was done with the right hand, the Agency subscale was higher when the hand avatar was used compared to the abstract avatar.

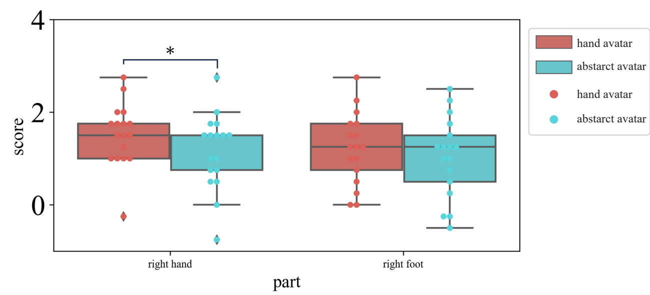
4.3 Summary of findings

The main facts revealed by the experiment are as follows.

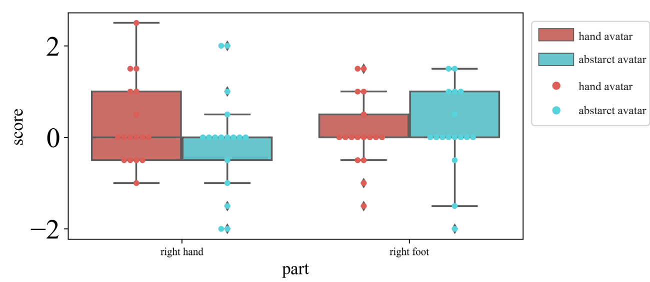
1. When the VR avatar was redirected medially or laterally, the threshold for redirection was approximately 21% larger when the hand avatar was used than when an abstract avatar was used.
2. When the VR avatar was redirected medially, the threshold for redirection was about 49% larger than when the VR avatar was redirected laterally, regardless of the body part used for manipulation.
3. There was no significant difference in threshold for redirection by the difference of the body part used for manipulation.



(a) Ownership subscale



(b) Agency subscale



(c) Location subscale

Fig. 10: Results of the embodiment questionnaire. Agency subscale (b) showed higher questionnaire scores for the hand avatar only when they were operated with the right hand. On the other hand, Ownership subscale (a) and Location subscale did not show significant differences between conditions. *: $p < 0.05$.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3549161

4. Only when the VR avatar was manipulated with the right hand, the Agency subscale of the sense of embodiment was improved the closer the VR avatar's appearance was to the hand. On the other hand, there was no significant difference in the sense of embodiment of the VR avatar due to differences in the body part used to manipulate the VR avatar.

5 Discussion

In this experiment, we found for the first time that when a VR avatar is manipulated away from the real body, the avatar's appearance affects the threshold on redirection, regardless of the body part being manipulated.

Even when the body part used for manipulation was the foot, the avatar's appearance was hand-shaped, but we observed the same increase in threshold for redirection as when the avatar was manipulated by hand. In addition, there was no significant difference in the magnification of the increase in threshold on redirection when the avatar was manipulated by hand or by foot. These results suggested that whether the appearance of the avatar matches the actual body part being used for manipulation might not be a contributing factor to the redirection detection threshold. The results also suggested that the level of abstraction in appearance can affect the threshold. Therefore, in motor inputs involving body parts other than the hand, using an appropriate appearance for the avatars, such as making it resemble a human body, may reduce the sense of discomfort when intervening in the movement. However, recent studies have suggested that the realism of an avatar or its resemblance to the body may not influence redirection detection thresholds [5, 13]. To investigate the causes of these discrepancies, it would necessary to conduct experiments with more detailed and segmented conditions.

We found that redirection in the medial direction resulted in a higher detection threshold compared to redirection in the lateral direction. In the redirection detection task, participants needed to move their actual body in a way that compensates for the positional shift caused by the redirection. In other words, the body part performing the reaching movement in the real world needed to be moved laterally in cases of medial redirection, and vice versa for lateral redirection. One of the reasons why the threshold is higher in the case of medial redirection than in the case of lateral redirection might be that the body part used for manipulation crosses the center of the body in the case of lateral redirection. Since the body has a fundamentally symmetrical structure, proprioception may be highly sensitive to whether the limbs are crossing the body midline. As a result, during sensory integration, the discomfort from proprioception may have outweighed the visual information, leading to a lower detection threshold. However, whether the body truly possesses such a characteristic would need to be confirmed through more detailed experiments.

Peripersonal space (the space near the body) may be one of the factors contributing to this difference. It has been reported that the characteristics of peripersonal space differ from those of the space lateral it, in terms of sensory integration and reaction time to stimuli [27–29]. For example, in the rubber hand illusion, it has been suggested that the illusion weakens when the dummy hand is farther from the body's midline [31].

Furthermore, flexion and extension of the body part may help the explanation. In our experiment, when no redirection was applied, participants' elbows or knees did not fully extend when they touched the target object with their hands or feet. Under the medial redirection condition, the elbows and knees also remained flexed. However, under the lateral redirection condition, where the body part performing the reaching movement had to be moved medially, participants' elbows and knees were often fully extended. Sensory integration may be influenced by proprioceptive sensations related to the flexion/extension of these body joints.

Ogawa et al. [30] also performed a similar task. In this experiment, only the right hand was used and there was no vertical offset, but the initial position was 100 mm to the right of the participant's body midline (i.e., in front of the right hand). The results of this previous study showed that the detection threshold for lateral redirection was higher than that for medial redirection. Although this result appears to be the opposite of our experimental results, it would be consistent when considering the range of motion of the body as discussed above. Furthermore, the result showing an increase in detection thresholds when redirected in the medial direction is generally consistent with trends observed in several previous studies. For example, studies by Zenner et al. [40] and Lebrun et al. [24] reported higher detection thresholds when a reaching task was performed using the right hand and remapped to the left (medial) side.

Regarding the subjective experience of embodiment, although a significant difference in the threshold was observed due to the difference in the avatar's appearance, no significant difference was found in the Ownership and Location subscales. This result is consistent with several previous studies on the effect of avatar appearance differences on the sense of embodiment [26, 30]. Compared to [30], which conducted a similar experiment, the Ownership and Location subscales in our results tended to be lower. This difference may be due to the fact that our experiment involved the virtual offset and did not reflect fine postures such as fingertip movements. On the other hand, the Agency subscale was similar, suggesting that the offset and fine movement differences may not have a significant impact on the user's sense of agency on the VR avatar.

5.1 Limitation

While the experiment provided several findings, it is important to note that it has certain limitations. The gender imbalance in our dataset might have influenced the results and should be considered when interpreting the findings. In addition, in this experiment, the order of the body parts used for manipulation was the same for all participants (right hand, right foot, and left foot, in that order). Therefore, it cannot be completely ruled out that order effects may have influenced the results.

The realism of the avatars used in this study can also have a limitation. In our experiment, we employed a hand avatar that was white in color with fixed fingers. However, more realistic avatars, such as those matching the user's skin tone or allowing finger movement, may produce different results. Further detailed experiments are needed to investigate the relationship between the realism of the avatar and the body parts used for manipulation.

5.2 Future Work

In the hand avatar condition, the redirection detection threshold was higher than in the spherical avatar condition. While various factors, such as the motif of a 'human hand' itself or the size of the avatar, in addition to the similarity to the body part being used, could have contributed to this, the present experiment was unable to determine which specific factor—shape, size, motif, or others—affected the redirection threshold. However, by appropriately designing the appearance of the object or avatar reflecting the movement, it may be possible to adjust or modify the movement in a way that participants feel less discomfort with the redirection. Therefore, conducting more detailed experiments to clarify design guidelines for appearance in the context of redirection could be a promising future research topic.

In our redirection model shown in Figure 5, when participants performed a reaching movement, the VR avatar's motion begins to shift discontinuously at a certain angle once a specific point was passed. As a result, if this angle becomes too large, the discontinuous change may cause discomfort. Therefore, by improving the redirection model to a nonlinear one that allows for continuous changes, it may be possible to reduce participants' discomfort and improve the detection threshold for redirection.

Finally, although the feet were used as the body part for motion input other than the hands in this experiment, the application limits of redirection when applied to motion input using other body parts have not been investigated. In addition, although this study implemented a simple reaching task, the relationship between more complex tasks and sensory integration of movement inputs involving various body parts has not yet been fully elucidated. Further exploration of these relationships could provide deeper insights into optimizing redirection techniques for a wider range of interaction scenarios.

6 Conclusion

We conducted a reaching task to investigate the effects of movement inputs using different body parts, specifically the hands and feet, and the appearance of the manipulated avatar on the redirection detection threshold. We found that regardless of the body part on which the manipulation was performed, the threshold on redirection was approximately 21% greater when a hand-shaped avatar was used than when an abstract avatar was used. We also found that when the VR avatar was redirected medially, the threshold for redirection was about 49% larger than when the VR avatar was redirected laterally, regardless of the body part used for manipulation. These results may suggest that the accuracy of proprioception is influenced by physical characteristics such as the flexion and extension of body parts and their relationship to the body's midline, and that these factors should be considered in the design of redirection. Furthermore, it was suggested that the influence of visual appearance on the detection threshold for redirection may not depend on the body part to be manipulated. This suggests that the same influence on threshold for redirection can be achieved by adjusting the visual elements, even if the body part performing the manipulation differs. This study may serve as a starting point for future research that seeks to bridge movement inputs from various body parts with redirection techniques, paving the way for more comprehensive interaction designs.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP24K20814.

References

[1] K. Arai, H. Saito, M. Fukuoka, S. Ueda, M. Sugimoto, M. Kitazaki, and M. Inami. Embodiment of supernumerary robotic limbs in virtual reality. *Scientific reports*, 12(1):9769, 2022. 2

[2] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*, pp. 1968–1979, 2016. 2

[3] Y. Ban, T. Kajinami, T. Narumi, T. Tanikawa, and M. Hirose. Modifying an identified curved surface shape using pseudo-haptic effect. In *2012 IEEE Haptics Symposium (HAPTICS)*, pp. 211–216. IEEE, 2012. 2

[4] H. G. Debarba, R. Boulic, R. Salomon, O. Blanke, and B. Herbelin. Self-attribution of distorted reaching movements in immersive virtual reality. *Computers & Graphics*, 76:142–152, 2018. 2

[5] M. Feick, A. Zenner, S. Seibert, A. Tang, and A. Krüger. The impact of avatar completeness on embodiment and the detectability of hand redirection in virtual reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 1–9, 2024. 2, 8

[6] M. Fukuoka, F. Nakamura, A. Verhulst, M. Inami, M. Kitazaki, and M. Sugimoto. Sensory attenuation with a virtual robotic arm controlled using facial movements. *IEEE Transactions on Visualization and Computer Graphics*, 2023. 2

[7] M. Fukuoka, A. Verhulst, F. Nakamura, R. Takizawa, K. Masai, and M. Sugimoto. Facedrive: Facial expression driven operation to control virtual supernumerary robotic arms. In *SIGGRAPH Asia 2019 XR*, SA '19, 2 pages, p. 9–10. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3355355.3361888 2

[8] S. Gallagher. Philosophical conceptions of the self: implications for cognitive science. *Trends in cognitive sciences*, 4(1):14–21, 2000. 2

[9] M. Gonzalez-Franco and T. C. Peck. Avatar embodiment. towards a standardized questionnaire. *Frontiers in Robotics and AI*, 5:74, 2018. 5, 6

[10] P. Haggard and V. Chambon. Sense of agency. *Current Biology*, 22(10):R390–R392, 2012. doi: 10.1016/j.cub.2012.02.040 2

[11] J. Han, J. Anson, G. Waddington, and R. Adams. Proprioceptive performance of bilateral upper and lower limb joints: side-general and site-specific effects. *Exp. Brain Res.*, 226(3):313–323, May 2013. 1

[12] J. Hartfill, J. Gabel, L. Kruse, S. Schmidt, K. Riebandt, S. Kühn, and F. Steinicke. Analysis of detection thresholds for hand redirection during Mid-Air interactions in virtual reality. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, number Article 35 in VRST '21, pp. 1–10. Association for Computing Machinery, New York, NY, USA, Dec. 2021. 1

[13] J. Hartfill, M. Schrader, and F. Steinicke. Investigating the impact of virtual hand realism on embodiment and redirection sensitivity in virtual reality. In *GI VR/AR Workshop*, pp. 10–18420. Gesellschaft für Informatik eV, 2024. 2, 8

[14] D. Hayashi, K. Fujita, K. Takashima, R. W. Lindeman, and Y. Kitamura. Redirected jumping: Imperceptibly manipulating jump motions in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 386–394. IEEE, 2019. 2

[15] J. Hernandez Sanchez, W. Amanhoud, A. Billard, and M. Bouri. Enabling four-arm laparoscopic surgery by controlling two robotic assistants via haptic foot interfaces. *The International Journal of Robotics Research*, p. 02783649231180366, 2023. 2

[16] A. Jackowski, M. Gebhard, and R. Thietje. Head motion and head gesture-based robot control: A usability study. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(1):161–170, 2017. 1, 2

[17] P. Kieliba, D. Clode, R. O. Maimon-Mor, and T. R. Makin. Robotic hand augmentation drives changes in neural body representation. *Science Robotics*, 6(54):eabd7935, 2021. doi: 10.1126/scirobotics.abd7935 2

[18] K. Kilteni, R. Groten, and M. Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012. 2

[19] K. Kilteni, A. Maselli, K. P. Kording, and M. Slater. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in human neuroscience*, 9:141, 2015. 2

[20] L. Kohli. Redirected touching: Warping space to remap passive haptics. In *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 129–130, 2010. doi: 10.1109/3DUI.2010.5444703 2

[21] L. Kohli, M. C. Whitton, and F. P. Brooks. Redirected touching: The effect of warping space on task performance. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 105–112. IEEE, 2012. 1

[22] R. Kondo, Y. Tani, M. Sugimoto, K. Minamizawa, M. Inami, and M. Kitazaki. Re-association of body parts: Illusory ownership of a virtual arm associated with the contralateral real finger by visuo-motor synchrony. *Frontiers in Robotics and AI*, 7, 2020. doi: 10.3389/frobt.2020.00026 2

[23] K. Kunio, M. Masando, and I. Issei. [definition of dominant hand and dominant foot] kikite kikiashi no teigi ni tsuite(in japanese). *Physical Education Research*, 10(2):224, 1966. doi: 10.5432/jjpehss.KJ00003394835 4

[24] F. Lebrun, S. Haliyo, and G. Bailly. A trajectory model for desktop-scale hand redirection in virtual reality. In C. Ardito, R. Lanzilotti, A. Malizia, H. Petrie, A. Piccinno, G. Desolda, and K. Inkpen, eds., *Human-Computer Interaction – INTERACT 2021*, pp. 105–124. Springer International Publishing, Cham, 2021. 8

[25] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet. Pseudo-haptic feedback: Can isometric input devices simulate force feedback? In *Proceedings IEEE Virtual Reality 2000 (Cat. No. 00CB37048)*, pp. 83–90. IEEE, 2000. 2

[26] L. Lin and S. Jörg. Need a hand? how appearance affects the virtual hand illusion. In *Proceedings of the ACM symposium on applied perception*, pp. 69–76, 2016. 8

[27] D. M. Lloyd. Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and cognition*, 64(1):104–109, 2007. 8

[28] T. R. Makin, N. P. Holmes, and H. H. Ehrsson. On the other hand: dummy hands and peripersonal space. *Behavioural brain research*, 191(1):1–10, 2008. 8

[29] J.-P. Noel, M. Samad, A. Doxon, J. Clark, S. Keller, and M. Di Luca. Peripersonal space as a prior in coupling visual and proprioceptive signals. *Scientific reports*, 8(1):15819, 2018. 8

[30] N. Ogawa, T. Narumi, and M. Hirose. Effect of avatar appearance on detection thresholds for remapped hand movements. *IEEE Transactions on Visualization and Computer Graphics*, 27(7):3182–3197, 2021. doi: 10.1109/TVCG.2020.2964758 1, 2, 3, 4, 6, 8

[31] C. Preston. The role of distance from the body and distance from the real hand in ownership and disownership during the rubber hand illusion. *Acta psychologica*, 142(2):177–183, 2013. 8

[32] D. Rakita, B. Mutlu, and M. Gleicher. A motion retargeting method for effective mimicry-based teleoperation of robot arms. In *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pp. 361–370, 2017. 1, 2

[33] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. 2001. 2

[34] I. Rock and J. Victor. Vision and touch: An experimentally created conflict between the two senses. *Science*, 143(3606):594–596, 1964. 1, 2

[35] M. Y. Saraiji, T. Sasaki, K. Kunze, K. Minamizawa, and M. Inami. Metaarms: Body remapping using feet-controlled artificial arms. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pp. 65–74, 2018. 1, 2

[36] T. Sasaki, M. Y. Saraiji, C. L. Fernando, K. Minamizawa, and M. Inami. Metalimbs: Multiple arms interaction metamorphism. In *ACM SIGGRAPH 2017 emerging technologies*, pp. 1–2. 2017. 1, 2

[37] H. Shimobayashi, T. Sasaki, A. Horie, R. Arakawa, Z. Kashino, and M. Inami. Independent control of supernumerary appendages exploiting upper limb redundancy. In *Proceedings of the Augmented Humans International Conference 2021*, pp. 19–30, 2021. 2

[38] J. Spillmann, S. Tuchschmid, and M. Harders. Adaptive space warping to enhance passive haptics in an arthroscopy surgical simulator. *IEEE transactions on visualization and computer graphics*, 19(4):626–633, 2013. 1

[39] K. Umezawa, Y. Suzuki, G. Ganesh, and Y. Miyawaki. Bodily ownership of an independent supernumerary limb: an exploratory study. *Scientific Reports*, 12:2339, 02 2022. doi: 10.1038/s41598-022-06040-x 2

[40] A. Zenner and A. Krüger. Estimating detection thresholds for desktop-scale hand redirection in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 47–55. IEEE, 2019. 1, 2, 3, 8

[41] J. Zhang, M. Huang, R. Yang, Y. Wang, X. Tang, J. Han, and H.-N. Liang. Understanding the effects of hand design on embodiment in virtual reality. *AI EDAM*, 37:e10, 2023. 2